A Metro-Access Integrated Network with All-Optical Virtual Private Network Function Using DPSK/ASK Modulation Format

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Abstract

All-optical virtual private network (VPN), which offers dedicated optical channels to connect users within a VPN group, is considered a promising approach to efficient internetworking with low latency and enhanced security implemented in the physical layer. On the other hand, time-division multiplexed (TDM) / wavelength-division multiplexed (WDM) network architecture based on a feeder-ring with access-tree topology, is considered a pragmatic migration scenario from current TDM-PONs to future WDM-PONs and a potential convergence scheme for access and metropolitan networks, due to its efficiently shared hardware and bandwidth resources. All-optical VPN internetworking in such a metro-access integrated structure is expected to cover a wider service area and therefore is highly desirable. In this paper, we present a TDM/WDM metro-access integrated network supporting all-optical VPN internetworking among ONUs in different sub-PONs based on orthogonal differential-phase-shift keying (DPSK) / amplitude-shift keying (ASK) modulation format. In each ONU, no laser but a single Mach-Zehnder modulator (MZM) is needed for the upstream and VPN signal generation, which is cost-effective. Experiments and simulations are performed to verify its feasibility as a potential solution to the future access service.

Keywords: All-optical virtual private network, optical access network, passive optical network (PON), scalability.

1. INTRODUCTION

All-optical virtual private network (VPN) is considered a promising approach to high throughput and enhanced security for access users. It has been demonstrated in conventional passive optical networks (PONs) [1, 2] and in two-stage PONs [3]. On the other hand, a time-division multiplexed (TDM)/wavelength- division multiplexed (WDM) network based on a feeder-ring with access-trees is considered a potential convergence scheme for access and metropolitan networks, due to efficiently shared bandwidth and hardware resources [4]. VPN service in such a metro-access integrated structure is expected to cover a wider area and therefore is highly desired.

In this paper, we propose and demonstrate a metro-access integrated network enabling all-optical VPN functionality, which consists of a single-fiber ring with tree sub-PONs attached to it. The proposed architecture features (1) orthogonal differential-phase-shift keying (DPSK) / amplitude-shift keying (ASK) modulation format for simultaneous downstream and VPN data transport, and bidirectional VPN communication; (2) centralized light sources at the optical line terminal (OLT); (3) a single Mach-Zehnder modulator (MZM) in each optical network unit (ONU) for both upstream [5] and VPN data encoding. Compared to the proposal in [6], this scheme eliminates the light sources and Mux/Demux in the ONU, which simplifies the structure. Furthermore, we investigate the performance of the DPSK multiplexing technique by experiment and its scalability by simulations.

2. PRINCIPLE AND ARCHITECTURE

Fig. 1 shows the generic architecture of the proposed TDM/WDM metro-access integrated network. The sub-PONs are time-division multiplexed, and in each sub-PON, ONUs are multiplexed in a WDM manner via an $N \times N$ arrayed waveguide grating (AWG) in the remote node (RN). The downstream DPSK signals and upstream carriers are generated at the OLT, and terminated after traversing the ring once. They are allocated in different wavebands defined by the FSR

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of the AWGs, as shown in Fig. 1, and are routed to the corresponding ONUs by the AWGs. Note that all the AWGs have the same FSR. Fig. 2~4 show the structure of a sub-PON including an RN and *N* ONUs with the traffic flows indicated. The ONUs at the same wavelength in different sub-PONs can be grouped to form a VPN.

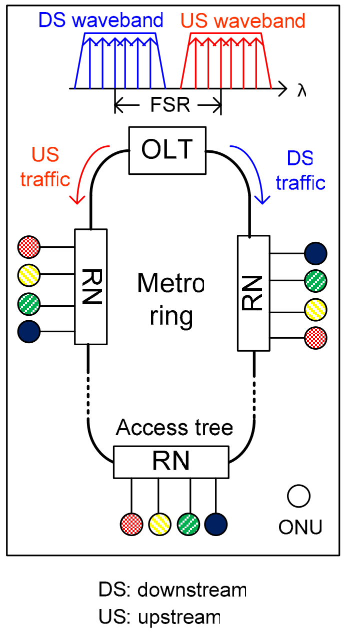

Fig. 1. Generic architecture of the metro-access integrated network.

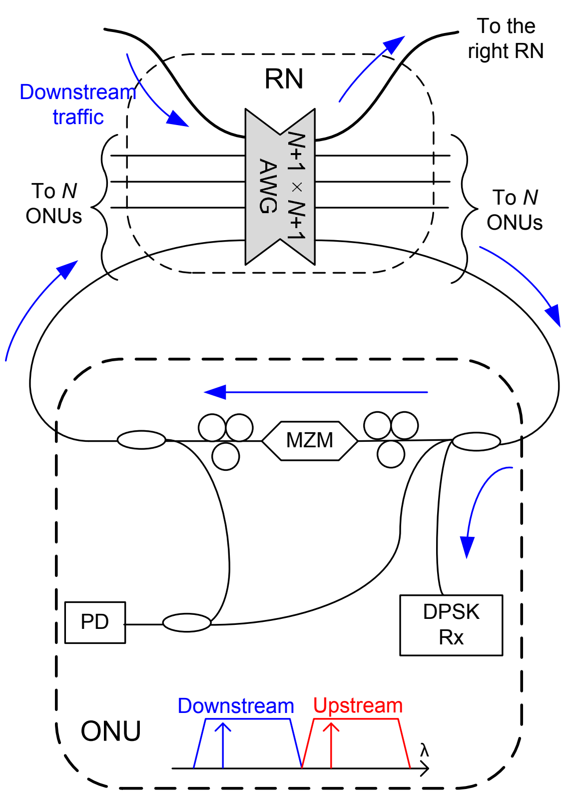

Fig. 2. Structure of a sub-PON with downstream traffic indicated.

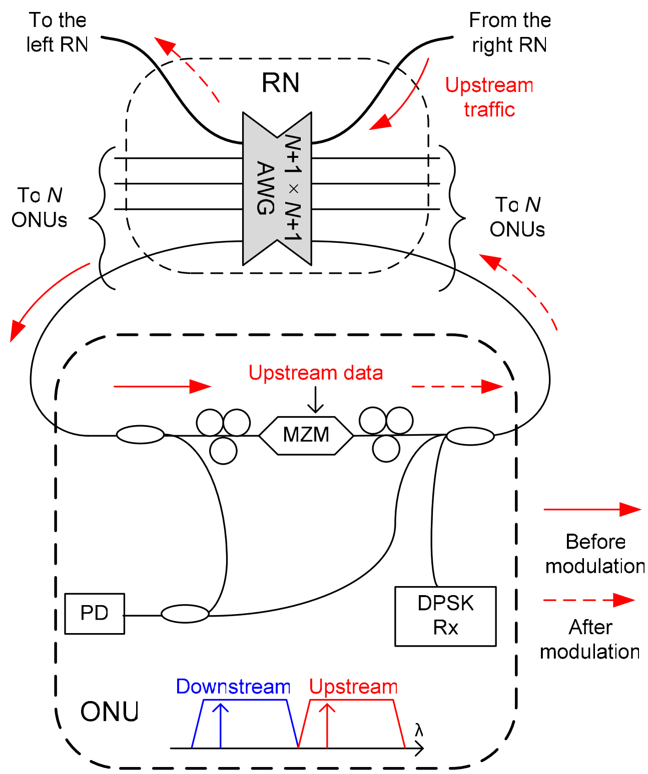

Fig. 3. Structure of a sub-PON with upstream traffic indicated.

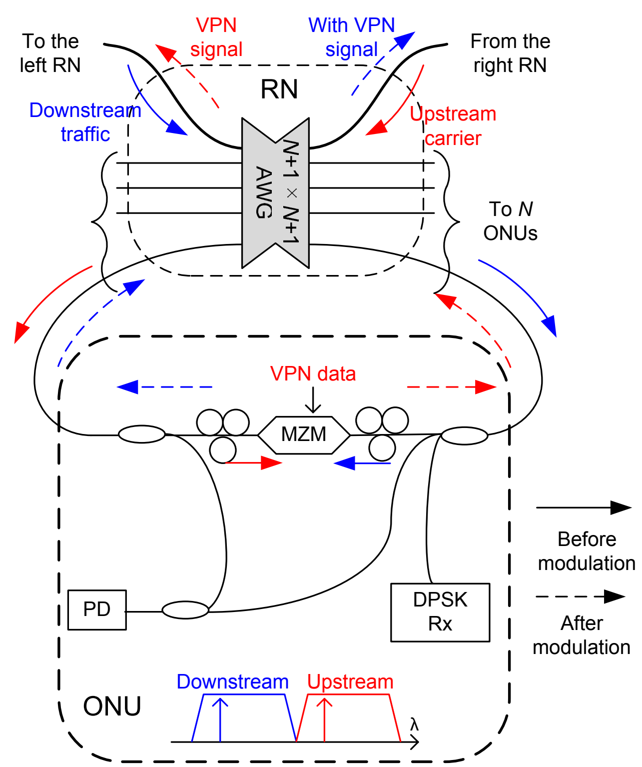

Fig. 4. Structure of a sub-PON with VPN traffic indicated.

In an ONU, a part of the downstream DPSK signal is tapped for detection, and the rest is sent to the MZM ready for VPN data encoding before moving on to the next ONU. For upstream signal generation in each ONU, a coherent DPSK signal multiplexing technique is employed. Fig. 5 shows the principle of this technique, where an optical carrier passes two phase modulators consecutively. With half-bit time shift between Data1 and Data2, phase transitions (information) carried by them are multiplexed. As a result, a coherent DPSK signal with twice the bit rate is generated [5]. The technique can be extended to multiplex data streams from M consecutive ONUs with a time shift of bit-duration/M. In the end, the multiplexed upstream DPSK signal is demodulated by a high-speed DPSK receiver at the OLT, and data from each ONU is demultiplexed. Since both the downstream and upstream data pass through the same MZM in an ONU, they should be scheduled in different time slots to avoid interference.

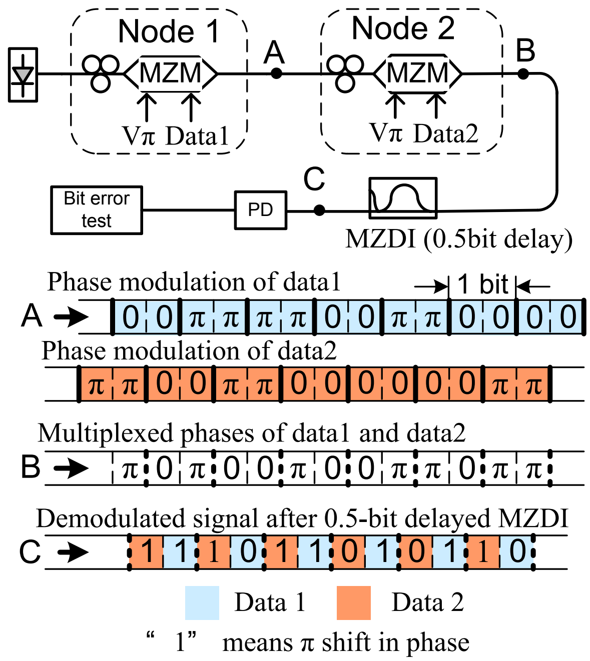

Fig. 5. Structure of a sub-PON with VPN traffic indicated.

In the time slots of downstream signal, the VPN data in ASK format can be simultaneously encoded on the counter-propagating downstream DPSK signal and upstream carrier (Fig. 4), so that the VPN signal can be transmitted in both directions and received by all the ONUs in the same VPN. The photodetector (PD) in the ONU is set up for bidirectional detection. To avoid contention, the traffic within the same VPN should be scheduled in a TDM manner.

To meet the power budget and to maximize cascadability, a bidirectional Erbium-doped fiber amplifier can be inserted in each RN to compensate for the power losses.

3. EXPERIMENT

We experimentally verify the feasibility of the proposed TDM/WDM metro-access integrated network with all-optical VPN function. The down-/upstream traffic at the wavelengths of 1547.58 nm and 1553 nm respectively are generated by using independent 5-Gb/s data streams with a pseudo-random bit sequence (PRBS) length of 2^{31}-1. The VPN traffic is a 625-Mb/s data stream with a PRBS length of 2^{7}-1.

Firstly, we experimentally test the coherent DPSK signal multiplexing technique as shown in Fig. 5. Fig. 6(a) depicts the eye diagram and bit error rate (BER) measurements. The sensitivities for various misalignments between the two data streams ranging from -25 ps to +25 ps are measured as well, to investigate the technique's tolerance to the synchronization mismatch between nodes (Fig. 6(b)). Within ±10-ps misalignment, less than 1-dB penalty is observed.

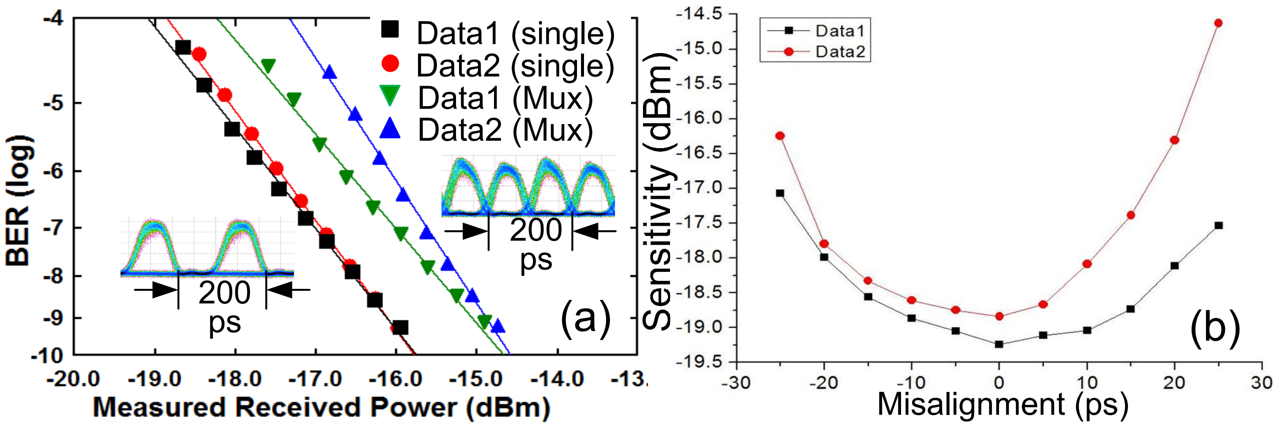

Fig. 6. (a) BER performances and eye diagrams of the DPSK multiplexing technology. (b) Sensitivities for various misalignments between the two data streams.

Next, the performance of the upstream transmission is investigated in a setup depicted by Fig. 7, where the upstream carrier is successively modulated by the MZMs in two different ONUs, and decoded by the DPSK receiver at the OLT, which consists of a 100-ps-delay interferometer and a single-ended 9-GHz photodetector. Fig. 8 shows the BER performance and the eye diagram. Less than 1-dB power penalty is observed.

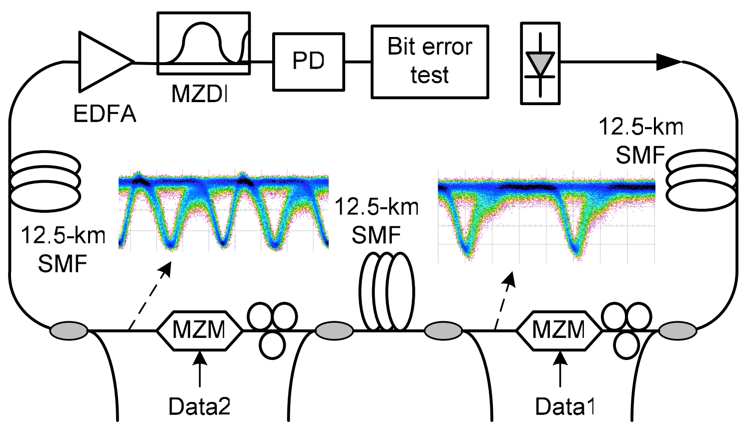

Fig. 7. Experimental setup for upstream transmission

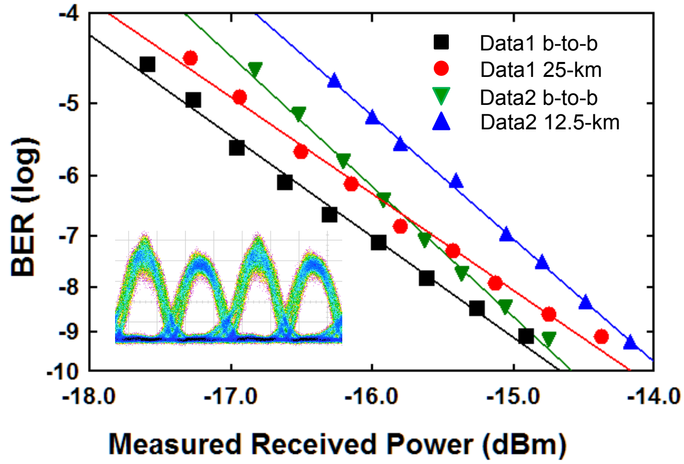

Fig. 8. BER performances of the upstream data with de-modulated eye diagram inserted.

Fig. 9 shows the setup for simultaneous transmission of VPN and downstream signals. The downstream DPSK signal and upstream carrier are both intensity modulated by the VPN data with an extinction ratio of ~4 dB. Fig. 10(1) illustrates the optical and electrical eye diagrams of the orthogonal ASK/DPSK signals. Fig. 10(b) show the BER measurements for the VPN and downstream signals.

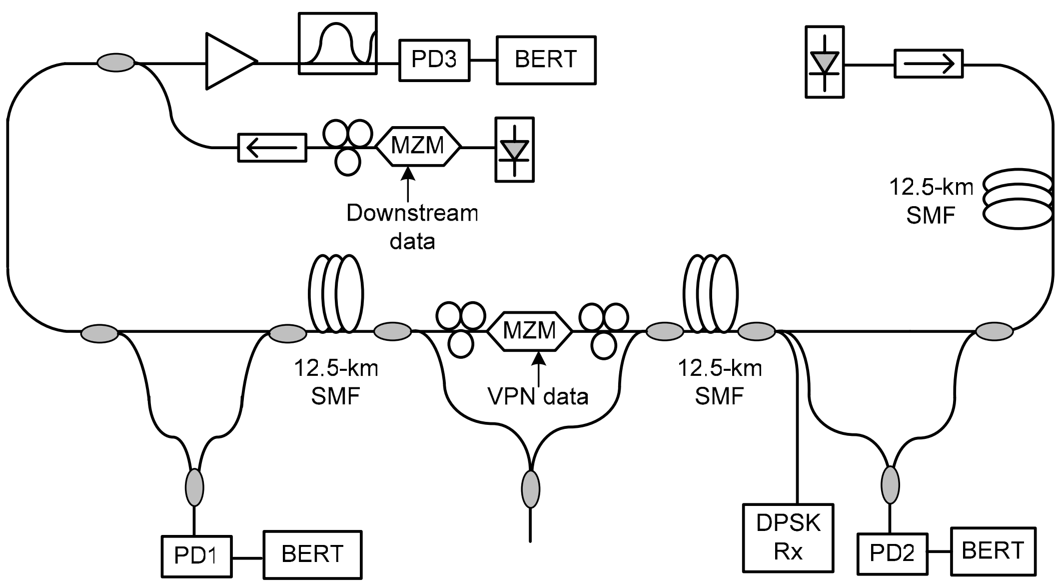

Fig. 9. Experimental setup for downstream and VPN transmission.

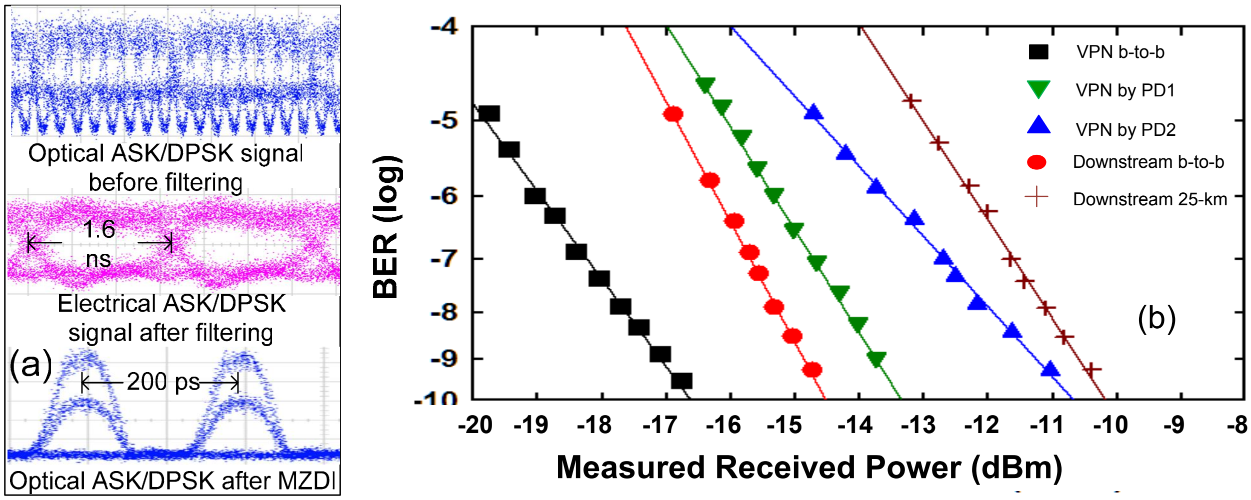

Fig. 10. (a) Eye diagrams of DPSK/ASK signal before and after filtering and after MZDI. (b) BER curves for VPN & downstream data.

Since the multi-node DPSK multiplexing technique determines the scalability of the proposed network, we investigate its performance via numerical modelling in which the same parameters as in the experiment are adopted. Fig. 11 depicts the simulated BER performance of two-node, four-node and eight-node cases. The results show that for 2 × 5-Gb/s multiplexing, the sensitivity is -15.4 dBm, which is close to the experimental measurement. The sensitivity is degraded by 2.7 dB for 4 × 2.5-Gb/s multiplexing, and by 6.3 dB for 8 × 1.25-Gb/s. For node spacing of 12.5 km, the penalty caused by transmission is less than 0.5 dB with dispersion and power loss compensated for. Therefore, the proposed network consisting of typical sub-PONs with 32 ONUs in each, can serve up to 256 ONUs in the eight-node case. In practice, avalanche photodetectors and forward error correction can be used to further improve the scalability.

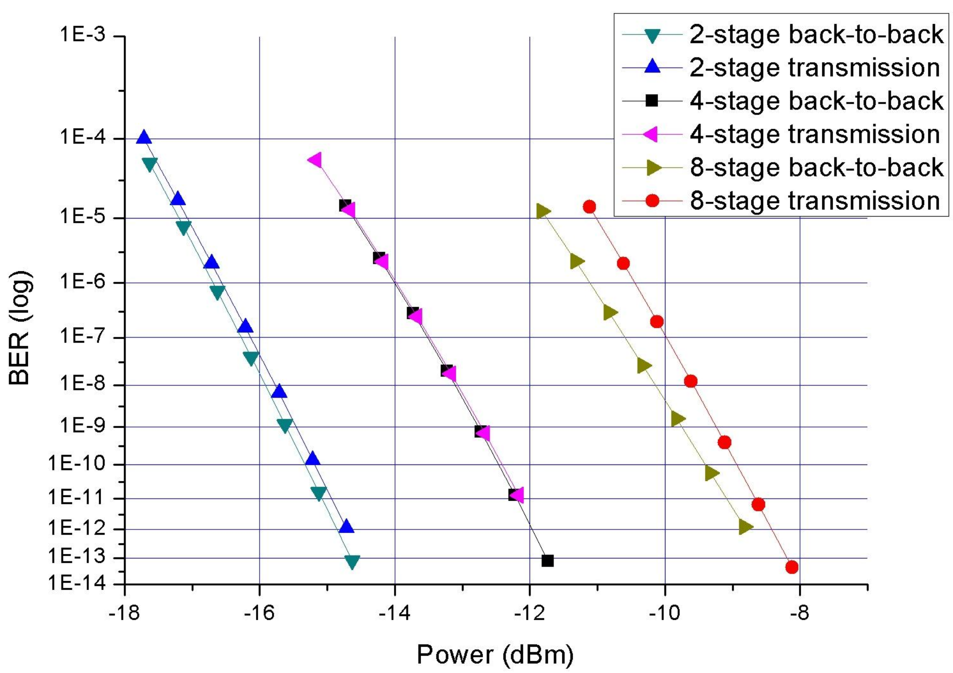

Fig. 11. (a) Eye diagrams of DPSK/ASK signal before and after filtering and after MZDI. (b) BER curves for VPN & downstream data.

4. CONCLUSIONS

We have proposed and demonstrated a TDM/WDM metro-access integrated network with all-optical VPN across different sub-PONs. Its feasibility as a potential solution for future access services has been verified by error-free transmissions and simulation analysis.

5. ACKNOWLEDGEMENT

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